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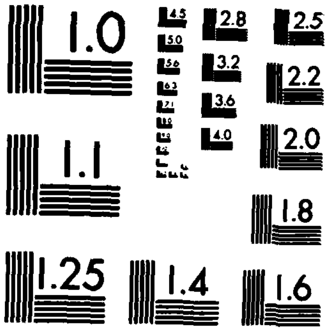

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AN IMPROVED NDE CAPABILITY FOR AEROSPACE COMPONENTS

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Technical Report

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The potential application of high resolution computed tomography (tomoscope) to non-destructive evaluations of aerospace components has been investigated. Trade-off studies of potential scan modes identified rotate-only scanning with a fiber-optic/Reticon Detector (SFRD) as the optimal approach to practical operation. Experimental studies of a microfocal x-ray source and the SFRD pinpointed current problems and capabilities. A conceptual design was developed as a recommended implementation of this technology. Concurrent source and prototype development was recommended as an appropriate approach to developing this technology.

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PREFACE

The authors would like to acknowledge the following important contributions to this effort:

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SECTION 1 INTRODUCTION

The Defense Nuclear Agency has, as a primary mission, the development of a data base that will lead to the improvement of the nuclear survivability of tactical and strategic military systems. In support of this nuclear hardening goal, DNA conducts an ambitious program of aboveground and underground nuclear weapons effects tests. In these tests, components, subsystems, and systems are tested to determine vulnerability modes and survivability limits. After an understanding is developed of the factors contributing to nuclear vulnerability, steps are taken to eliminate these factors or to reduce their impact.

Two primary types of nuclear vulnerability to missile systems and satellites are: 1) radiation-induced effects to the electrical/electronic subsystems (guidance, control, arming, fusing, etc.) and 2) thermomechanical damage to the missile structure. The electrical/electronic effects can arise either from direct radiation deposition in critical electronic components or from effects arising from systems-generated electromagnetic pulse (SGEMP) -induced fields and currents in cables and components. The thermomechanical effects include structural motion that can damage critical components and cause mechanical damage to overlays and the heat shield, which can lead to targeting inaccuracies or failure during re-entry.

To properly address these and other vulnerability problems, DNA requires an improved capability for non-destructively evaluating the material and structural integrity of a test object prior to exposure in underground or aboveground nuclear tests and then for analyzing, in detail, the nuclear-induced damage to the material or structure. An ideal non-destructive evaluation (NDE) technique would be one that can be applied to a wide range of materials, is able to resolve small defects, can size and locate in three dimensions, and can provide the information in an unambiguous format. With such an NDE capability, the results from performance tests conducted after a nuclear-effects exposure (e.g. ablation tests of missile structures) could be correlated with both the pre-exposure quality of the material and with the characteristics of the damage induced by the nuclear tests.

Another important application of such an NDE capability would be for verification that hardening procedures are being followed. For example, satellite cables could be examined to insure that the void content in the dielectric is within an acceptable level, since it has been determined that high-void content leads to high-sensitivity to SGEMP effects.

This project has addressed the development of an improved NDE instrument, an x-ray tomoscope with features specifically designed to meet DNA NDE requirements. This x-ray tomoscope, which is based on computed-tomography (CT) principles, is expected to have the properties previously attributed to the "ideal" NDE instrument, including the ability to provide accurate, high-resolution images in three dimensions of defects/damage in a wide range of materials. The name "x-ray tomoscope" derives from the fact that this CT-based instrument possesses some of the properties that would be found in an x-ray microscope, if such were available.

The objectives of the tomoscope project were the development of a conceptual design of a tomography unit for the evaluation of small objects to fine spatial resolution (10 to 100 microns), the survey of appropriate sources and detectors to determine candidates for inclusion in such a unit, the experimental evaluation of selected sources and detectors to determine their effectiveness in the proposed design, and the assessment of the applicability of the design to non-destructive evaluations particularly with regard to radiation hardening of cables and material samples from underground tests.

The eventual capabilities of a high resolution tomography unit will be essentially determined by the characteristics of the source and detector. The design concept, however, is strongly driven by the choice of detector technology. Our survey of available detectors identified one candidate--the scintillator-fiber-optic Reticon detector (SFRD)-- which appears optimal for the first generation of high-resolution tomography.

Tomographic reconstruction at this level requires the extraction of prodigious quantities of x-ray transmission samples of the target object. To hold scan times down to practical levels, it is essential to obtain this

information as efficiently as possible. The SFRD allows the detector plane to be paved with high resolution detection elements thus optimizing throughput, while providing resolution which is well matched to sources which will be available in the foreseeable future. The simplified scan geometry (rotate-only) is an additional benefit which falls out of the most appropriate design concept.

After determining the basic design strategy, the most promising source (the TFI/Scanning microfocus x-ray source) was selected and a detector procured for experimental evaluations. The experimental studies provided valuable experience and information about the source and detector, though operational problems with the source prevented addressing the full range of parameters desired.

Investigation of potential applications indicates that evaluations of UGT samples and solder connections in chip-carrier vias should be addressable with a first generation tomoscope. Detection of shield/dielectric voids in radiation hardened cables may require further refinement of instrumental resolution.

In the next section (2) of this report, we will look at the trade-off analysis of the design options which served as the basis of the design concept. Section 3 will review the experimental studies of the source and detector and summarize what is and is not now known regarding their levels of performance, and what is required before a prototype instrument can be developed.

Section 4 addresses the applications of the proposed design to specific candidates for NDE testing. Section 5 will discuss the specific components of the design and the issues to be adressed in the production of a prototype unit. The final section (6) will provide a summary overview and recommendations for further development of this technology.

SECTION 2 TRADE-OFF STUDIES

Detailed trade-off studies were conducted to determine the most practical tomoscope design. Two scan geometries, translate-rotate and rotate-only, were considered.

The translate-rotate scan geometry is illustrated in Figure 2.1. Scans are performed by translating the object from a position outside the x-ray fan to a corresponding position on the opposite side of the beam. Arbitrarily fine linear samples at the discrete angular orientation associated with each detector element can be collected with this method. After a traverse, the object table is rotated by an amount equal to the fan angle, and the object is translated in the opposite direction. This process is repeated until 180 degrees of view have been collected. The data is then passed to the reconstruction program for processing. For overall versatility and reliability, the translate-rotate method of collecting scan data has been the geometry of choice since the inception of CT. The chief drawback with this method is that it takes longer to collect data than other approaches, becoming prohibitively slow as the size of the image matrix and the amount of data increases to tomoscopic levels.

The rotate-only geometry is illustrated in Figure 2.2. In this scheme there is no translational motion, only rotational. Consequently, the object of interest must be completely subtended by the fan of x-rays. Data is acquired at each rotary position until at least 180 degrees but more often 360 degrees of data have been collected. With this method, arbitrarily fine angular samples at the discrete radial positions associated with each detector element can be collected. Because only a single, highly-efficient scan motion is involved, scan times are significantly faster than with translate-rotate systems. On the down side, the size of objects that can be scanned is limited by the size of the x-ray fan angle, which is often subject to hardware constraints beyond the control of the designer.

Because translate-rotate systems sample chords through the object arbitrarily finely in the radial direction and rotate-only systems sample arbitrarily finely in the circumferential direction, these scan geometries

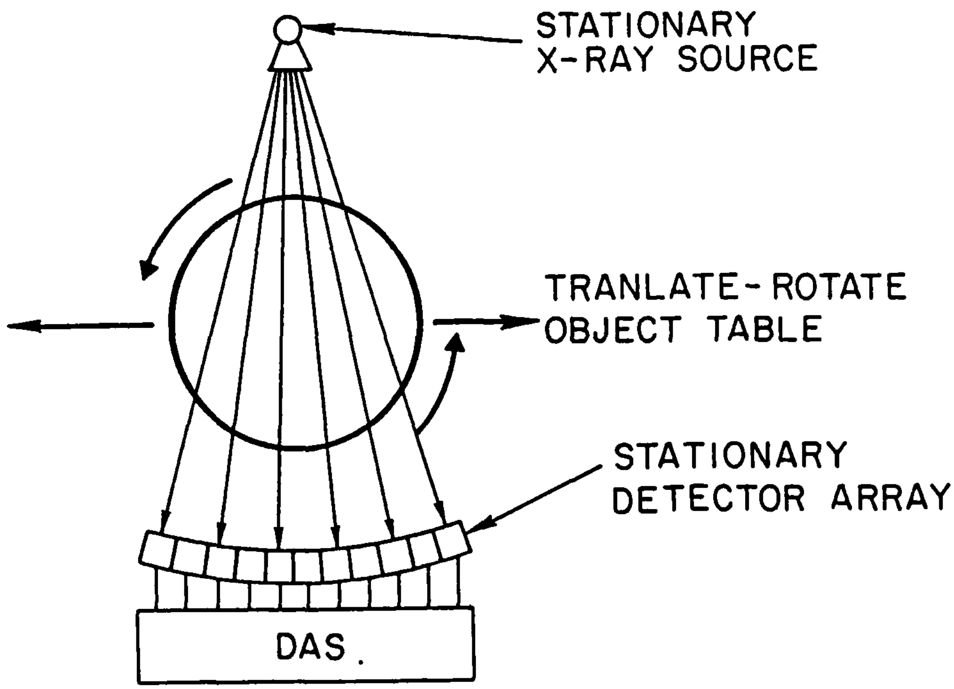

Figure 2.1 Translate-rotate scan geometry

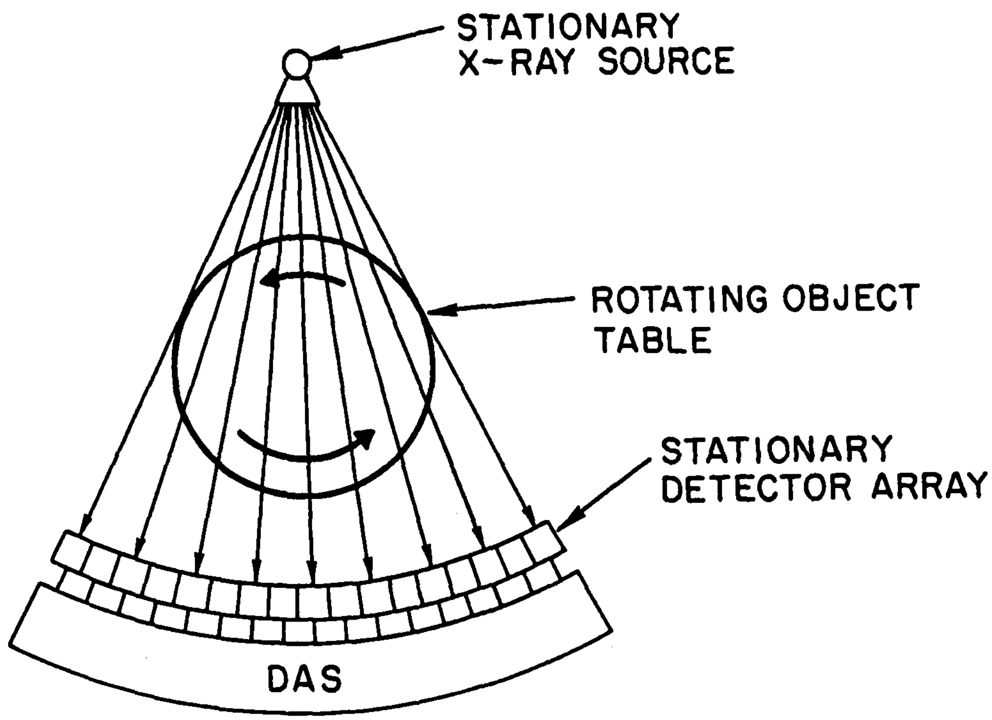

Figure 2.2 Rotate-only scan geometry

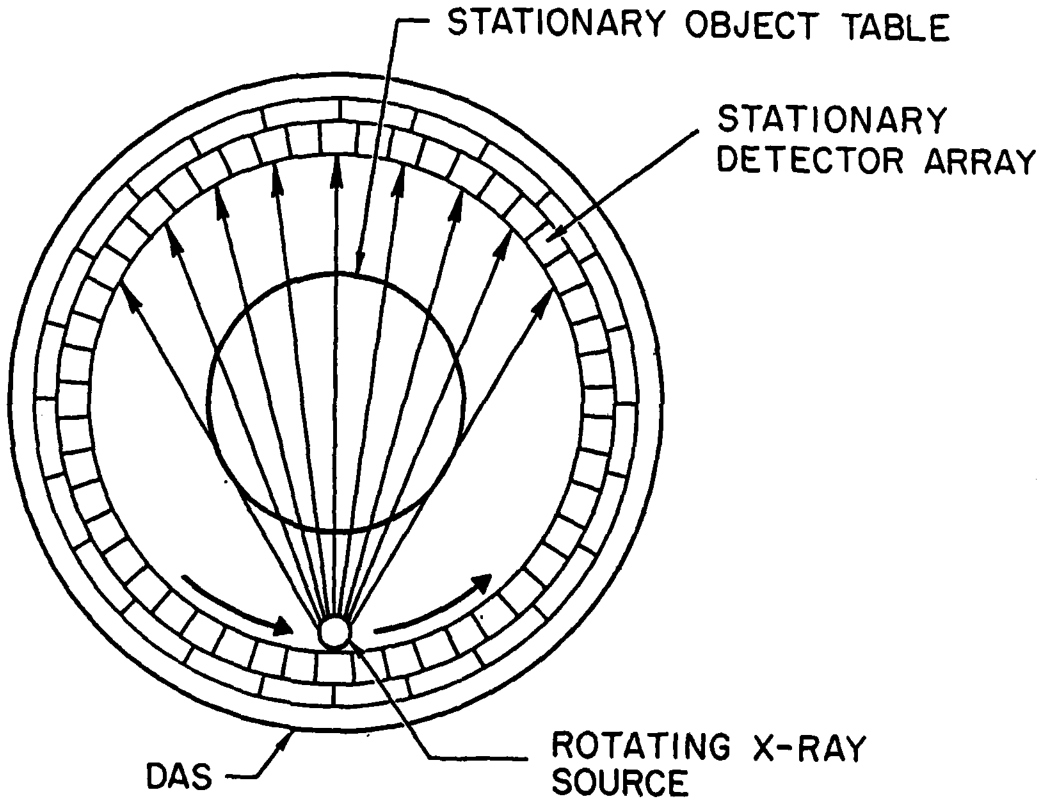

Figure 2.3 Rotating-source scan geometry

represent two mutually exclusive methods of collecting data. Other imaginable geometries can be thought of as linear combinations of these two "orthogonal" methods. Thus, all of the major design issues associated with various possible scan geometries can be expected to emerge from a detailed trade-off study of these two particular approaches.

In actual practice, only one other geometry is used to any extent: a rotate-only scheme utilizing a complete ring of stationary detectors and a rotating x-ray source (see Figure 2.3). This method is the single-motion version of the translate-rotate approach shown in Figure 2.1. Improvement in scan time by a factor of roughly two can be achieved with this approach, but at the expense of considerable flexibility because the object must now fit within the circular region defined by the rotation of the x-ray fan. This geometry was not studied because: (1) improvement in speed by a factor of two is not nearly enough to make scan times competitive with the rotate-only method; (2) flexibility is the principle advantage of the translate-rotate approach and as such should not be traded for what is, at best, a marginal improvement in throughput; and (3) this scheme introduces major engineering problems in the areas of scatter collimation, mechanical motions, and radiation safety.

2.1 Trade-off Parameters

The method of analysis used was to first develop detailed conceptual designs for translate-rotate and rotate-only systems and then to critically compare the two designs. The goal in both instances was to evolve the best possible overall design consistent with the stated objective of obtaining a resolution in the range of 25-100 microns a region of interest of 10 centimeters in diameter. Because these designs were developed over an extended period of time and have undergone numerous revisions, each represents a very mature conceptual approach which, if warranted, could be used as the basis for the detailed design of an actual system.

The issues which then emerged from a comparison of the two designs are presented in Table 2.1, along with pertinent comments. They are arbitrarily divided into two categories: (1) hardware-related issues and (2) software-

related issues. The hardware topics are subdivided into source, handling system, and detector issues. The software-related issues are categorized according to data gathering constraints, reconstruction ease, and artifact susceptibility.

2.2 Hardware Design Issues

The key issue that surfaced with regard to the x-ray source is that of intensity. CT images require that a certain well-defined number of photons be detected in order to generate results of a given statistical accuracy. Low intensities dictate longer signal integration times and, in turn, longer scan times. Consequently, because of current source technology limitations, the tomoscope is constrained to operate with the most intense microfocus source available. Currently, there are continuously pumped, replaceable-anode units. Even so, it would be desirable to increase source intensities by at least a factor of 25-50, indicating the need for additional development in the area of source technology. A preliminary review of existing units suggests that the required improvement may not be too difficult to engineer.

The hardware design issues that emerged with respect to the handling system are delineated in Table 2.1. The most important comparison is the scan times. The scan time calculated for the rotate-only approach is on the order of one hour with current source technology. The scan time calculated for the translate-rotate system for an equivalent image is roughly 25 hours, a major discrepancy. The other items are in some instances important but are generally less significant.

Comparing the detector-related issues, each approach can claim some advantages; but on the whole, the translate-rotate system offers the lowest-risk, highest resolution option---a major point in favor of this approach.

Table 2.1. Trade-off comparison of scan options (Rev. 5)

Design Issue/Parameter	Translate-Rotate	Rotate-Only
Hardware		
X-ray Source		
Intensity	inadequate	marginal
Handling System		
Mechanical Motion	100% overhead	no overhead
Scan Time	1 day	1 hour
Magnification	all M	depends on object size
On-line Cable Inspection	feasible	feasible
Vertical Geometry	feasible	feasible
Compression Filter	not feasible	feasible
Detection System		
Type	crystal/diode	fiber-optic/Reticon
Scatter Rejection	excellent	poor
Vertical Collimation	mechanical (difficult)	electronic (easy)
Cooling	not required	required
Stopping Power	excellent	good
Signal-Noise Ratio	good	good
Inter-Element Matching	excellent	probably acceptable
Technical Risk	low	moderate
Cost	acceptable	high
Dual-Energy Data	difficult	feasible
Software		
Data Gathering		
Temporary Storage Reqts.	N views	one view
Pipeline Processing	after each traverse	after each view
Reconstruction		
Algorithm	parallel beam	divergent beam
Fourier Compatibility	yes, with pipelining	yes, with rebinning
Artifact Susceptibility		
Tube Fluctuations	very susceptible	relatively immune
Detector Mismatches	relatively immune	very susceptible

2.3 Software Design Issues

With respect to data gathering, the translate-rotate approach requires that N views (where N is the number of detectors) be temporarily stored until the completion of a traverse, a restriction which delays data reduction slightly. The rotate-only scheme, on the other hand, can begin to reduce each view as soon as it is acquired, a small plus for the rotate-only system. Once the data has been reduced, it is submitted to the reconstruction algorithm. The translate-rotate system automatically collects data in a format that is amenable to several rapid reconstruction techniques. The rotate-only system, however, must reformat the data before it can take advantage of some of the faster algorithms. This reformatting can probably be performed during data collection but would be constrained to lag the data collection process by the time required for the system to rotate through an arc equal to the fan angle. This is a small plus for the translate-rotate approach. However, processing delays are not a major issue, and on the balance this is a draw.

The other item is artifact susceptibility. The translate-rotate scheme is very susceptible to tube fluctuations but is relatively immune to detector-to-detector mismatches. The situation reverses itself in the case of the rotate-only scheme. The tradeoff here depends on whether the designer expects tube fluctuations or detector-element mismatches to be the dominant engineering challenge. Based on the evidence presented here, it appears that tube fluctuations are the more dominant problem, a very strong point in favor of the rotate-only system.

2.4 Conclusions

As the result of a critical evaluation of the trade-offs associated with these issues, the following general conclusions were reached:

- If scan times were not a major consideration, the translate-rotate system would offer the greater flexibility and lower technical risk. Objects larger than the fan angle could be studied, the engineering uncertainties associated with the detector would be lower, and the ultimate spatial

resolution is theoretically better than that obtainable with the rotate-only system. However, available sources lack the intensity to make translate-rotate systems practical and, at this stage, this is not a viable option.

- o Available source intensities are marginally adequate for rotate-only systems, making this the only choice currently open. Spatial resolution, while in theory not intrinsically as good as the translate- rotate system, is at the present state of the art comparable to the translate- rotate approach; and the technical risks, while somewhat greater, appear to be manageable.

It is, therefore, the conclusion of this trade-off study that the rotate-only system, in spite of certain technical challenges, currently offers the only viable option. On the up-side, this approach has the best long-range prospect for providing a practical, high resolution CT system and consequently warrants the further attention being recommended.

SECTION 3 EXPERIMENTS AND EVALUATION

Experiments were performed using a ScanRay microfocus x-ray tube in the demonstration facility at the TFI Corporation in West Haven, Connecticut, during the period of October 30 through November 2, 1984.

The objective of the experiments was to provide characterization of the microfocus x-ray source, of the scintillator fiber-optice Reticon 1024 element detector (SFRD), and of the scintillator photodiode detector (SPD).

Upon arriving, we were informed by TFI that they had experienced a source failure, and that after installing some new parts, the source could not be focussed as well as it had been prior to the failure. They could not quantify the difference. Their previous focal spot size was estimated to be less than 10 microns, and as we estimated that 20 to 25 microns would be adequate for our measurements, we made the decision that it should be possible to perform the measurements with a non-optimum tube.

Unfortunately, the problem was more severe than just an oversize focal spot size. All of our measurements indicate that in addition to poor focus, a significant portion of the electron beam was striking the anode millimeters away from the focal spot. The imaging technique normally used by TFI to focus the electron beam is insensitive to a diffuse halo superimposed on the primary spot. The result of a diffuse source is to reduce the contrast of the image. For our purposes, the diffuse background severely reduces the resolution. Since we were told that the behavior observed was not characteristic of a normally operating tube, characterization of the source tells us little about the focal properties of a tube operating tube normally.

3.1 Source Characterization

The objectives of the source characterization were to evaluate the following:

- o Intensity;
- o Focal spot size;
- o Spectral characteristics;
- o Angular variation of intensity and spectrum;
- o Source stability, including
  - -spot size;
  - -spot position; and
  - -intensity.

The source characterizations which we were able to obtain were severely limited by three factors. The first of these was the abnormal performance of the source during the measurements. The second was a misunderstanding of the source capability. And the third was inadequate detector sensitivity.

With regard to the second problem, we understood that the tube could be operated at about 300 watts with a 25-micron focal spot, and most of our measurements were performed at this power level (150 kV, 2 ma). At this power level we experienced gross source instability both in quality of focus and in intensity. In addition, the x-ray intensity was not proportional to tube current, nor was it reproducible at the 2-mA current level. In Section 3.3 we discuss the probable limit of tube current.

Because the measured detector signals were lower than anticipated, there is reason to suspect that the measured current in these experiments may have been greater than the actual anode current. This implies that a fraction of the electrons were striking some portion of the tube structure other than the anode. If this was in fact the case, the detector sensitivity may not be as low as indicated in Section 3.2.

For the SPD detector which we intended to use for part of the source characterization measurements, typical signal levels with a 1.5 mm aperture were 0.1 volts. Since we intended to perform source-size measurements with this detector using an aperture no larger than 0.25 mm, the detector sensitivity was not adequate.

All of the source characterizations which were done used the SFRD whose sensitivity could be increased simply by increasing the integration time. The full 2-mm height of the scintillator was illuminated for all measurements.

Knife edge measurements were performed at the 2-mA source-current level using the SFRD. With the knife edge 18 cm from the source and the SFRD 50 cm from the source, the knife edge was moved across the x-ray beam in 0.125-mm steps. By subtracting the signals from two adjacent steps, we should obtain the source shape convolved with the detector resolution. The resulting signal exhibited a broad central peak with large asymmetric tails. This is illustrated in Figure 3.1 where two such difference signals are shown. The full-width-at-half-maximum (FWHM)of the central peak after correcting for the 0.125-mm motion of the knife edge was about 85 microns. The tail on the left extends about 130 microns. The tail on the right persists for nearly 2 mm. Since the detector response must be symmetric, the asymmetry of the signal can be attributed to the source. Assuming that all of the spread is due to the source, **we estimate that only approximately 20 percent of the x rays radiated from the central spot.**

In addition to the poor source focus, the intensity across the one-inch length of the SFRD varied as much as 20 percent. The character of the variation was dependent on the x-ray tube current. The implication is that parts of the extended source were being obscured at some positions in the three-degree arc subtended by the SFRD. Part of this obscuration may have been due to non-uniform tungsten deposits on the tube window. It was concluded that angular measurements would be meaningless while the source was in this condition.

Because of the low signal levels, the source instability, and the fact that the intensity was not proportional to the tube current, we did not attempt to perform the spectral measurements.

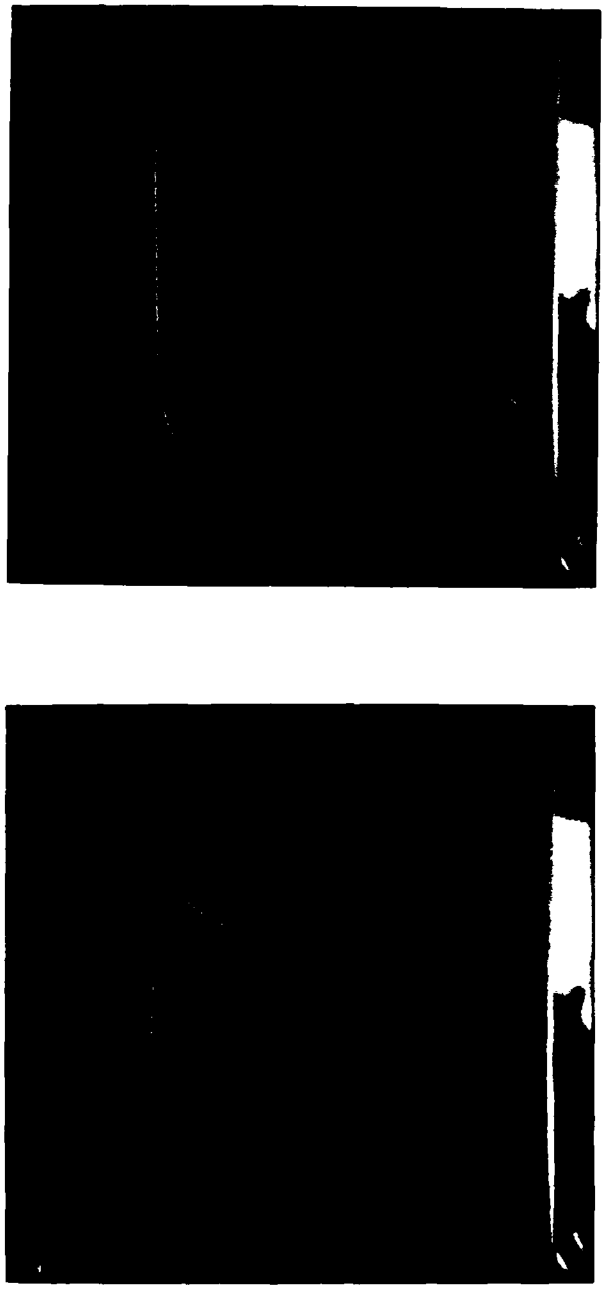

Figure 3.1. Differential Knife Edge Distribution

The measurements performed for the imaging experiment ultimately used an x-ray tube current of 0.2 mA. From these measurements, we were able to infer a mean photon energy of 70 to 80 keV. At this current, the source intensity was stable within the precision of our measurement (about 5 percent). By comparing scans of the hypodermic needle taken over a 10-minute interval, we conclude that the focal spot position was stable with refocussing to within about 50 microns. In addition, from the reproducible asymmetry of the scans, we can infer that the shape of the focus did not change significantly.

By simple modeling of the expected signal in the imaging experiment, the inferred shape of the focal spot at 0.2 mA was similar to that inferred from the knife edge measurements at 2 mA but a larger fraction of the x rays originated in the main spot at the lower current value.

3.2 Detector Characterization

The objectives of the detector characterization were to determine the following:

- Sensitivity of the SFRD and the SPD;
- Linearity of the SFRD;
- Spatial resolution of the SFRD;
- Dark current stability of the SFRD.

Measurements were made at ARACOR with a 30 mCi Americium source during the development of the CAMAC software for the computerized data acquisition. This source emits 26 and 60 keV photons in approximately equal numbers. The pixel-to-pixel variations in the SFRD signal when exposed to this source were essentially the same as the pixel-to-pixel noise variation--which was about 10 percent of the x-ray induced signal. The effective conversion efficiency measured with this source is approximately 3 keV per electron-hole pair.

Given the intensity obtained from the microfocus tube, the sensitivities of both the SPD and the SFRD are significantly lower than required to obtain scan data in a reasonable time. The typical SFRD signal level for these measurements

was about 0.45 volts with 3.2 second integration time and 2-mm slice thickness. The signal levels needed for practical scan times are discussed in Section 2.2.

The integrated dark current of the Reticon in the 3.2-second measuring time produced a signal of about 7.5 volts. The dark current is temperature sensitive and significant short term temperature fluctuations occurred in the radiation test cell in which the measurements were performed, producing dark current signal fluctuations of the order of 0.025 volts in time periods of minutes. Although this is only a 0.3 percent fluctuation in the dark current, it corresponds to a fluctuation of about 5 percent of the signal.

Since we cannot expect to improve the actual senstitivity significantly, additional amplification is required. In order to obtain an adequate signal-to-noise ratio, the dark current fluctuations must be reduced. This will require temperature stabilization of the Reticon. If the stabilization is done by cooling, a reduction of the magnitude of the dark current as well as its fluctuation can be achieved. The dark current is reduced by about a factor of 5 by reducing the temperature to zero degrees C, and is further reduced by an order of magnitude for each subsequent 20-degree reduction in temperature. Cooling to -40°C should produce an acceptably low dark current.

Because of the poor source performance, we were unable to measure either the linearity or resolution of the SFRD. We can ascribe a major portion of the width measured with the knife edge to the source rather than to the SFRD because broadening due to the SFRD must be symmetric.

The SPD signal can be readily increased by incorporating an integrator to enhance the signal level.

3.3 Pseudo-scan of the Hypodermic Needle

An additional experiment was planned to demonstrate the imaging capability of the source-detector combination. A normal computerized tomographic reconstruction requires a large number of angular views of the same object. The procedure is to scan the object, rotate it through a small angular increment and

repeat the scan until the object has been rotated through 180 degrees. In order to avoid the requirement for a precision rotating mechanism and its required alignments, the transmission measurements were to be performed on an object with cylindrical symmetry. This would allow a pseudo-reconstruction to be performed without actually rotating the test object.

The object chosen for the imaging tests consisted of a hypodermic needle inside a glass syringe (Figure 3.2). The syringe is a glass tube with 6.5-mm O.D. and 0.5-mm I.D. The needle is a steel tube with 0.45-mm O.D. and 0.15 mm I.D. Ten scans of this structure were obtained with the best focus of the x-ray tube which we were able to achieve at 0.2 mA tube current.

The unattenuated x-ray beam was measured with the SFRD. Then the test object was placed in the beam, and five (5) Reticon scans were performed in a total elapsed time of about 17 seconds. This procedure was repeated, adjusting the x-ray tube focus between each series. In order to obtain the ten reasonable scans (for adequate statistics), it was necessary to repeat the procedure about 50 times.

The reconstruction of the hypodermic is shown in Figure 3.3. Using simple modeling of the experiment we can make some statements about the spatial characteristics of the source. The fact that we can resolve the hole in the needle indicates that the central spot has an FWHM of 150 microns or less. In order to produce the distortion seen in the image of the glass tube, the source must also have a significant component with size comparable to the O.D. of the glass.

The image shown included a source deconvolution to symmetrize the raw data. The deconvolution process consisted of convolving the data with the assumed source function. A new data set was then constructed by subtracting the difference between the convolved data and the original data from the original data. The criterion for a reasonable deconvolution was the symmetry of the new data set, and the width of the needle image. The reconstruction was performed by using the same data set (a deconvolution of an average of the 10 best scans) for all of the angular views required by the reconstruction algorithm.

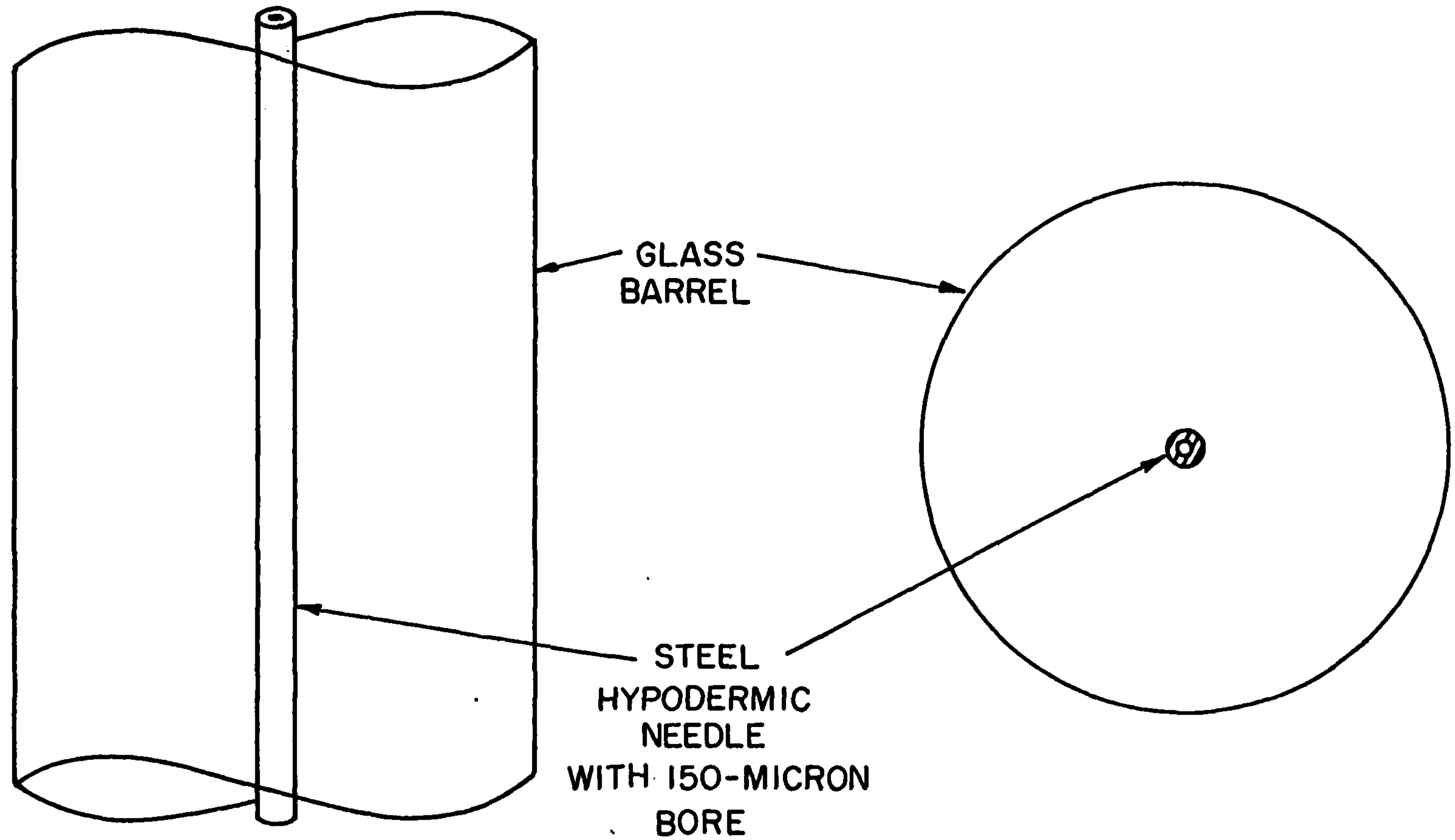

Figure 3.2 Microsyringe phantom used for tomograph

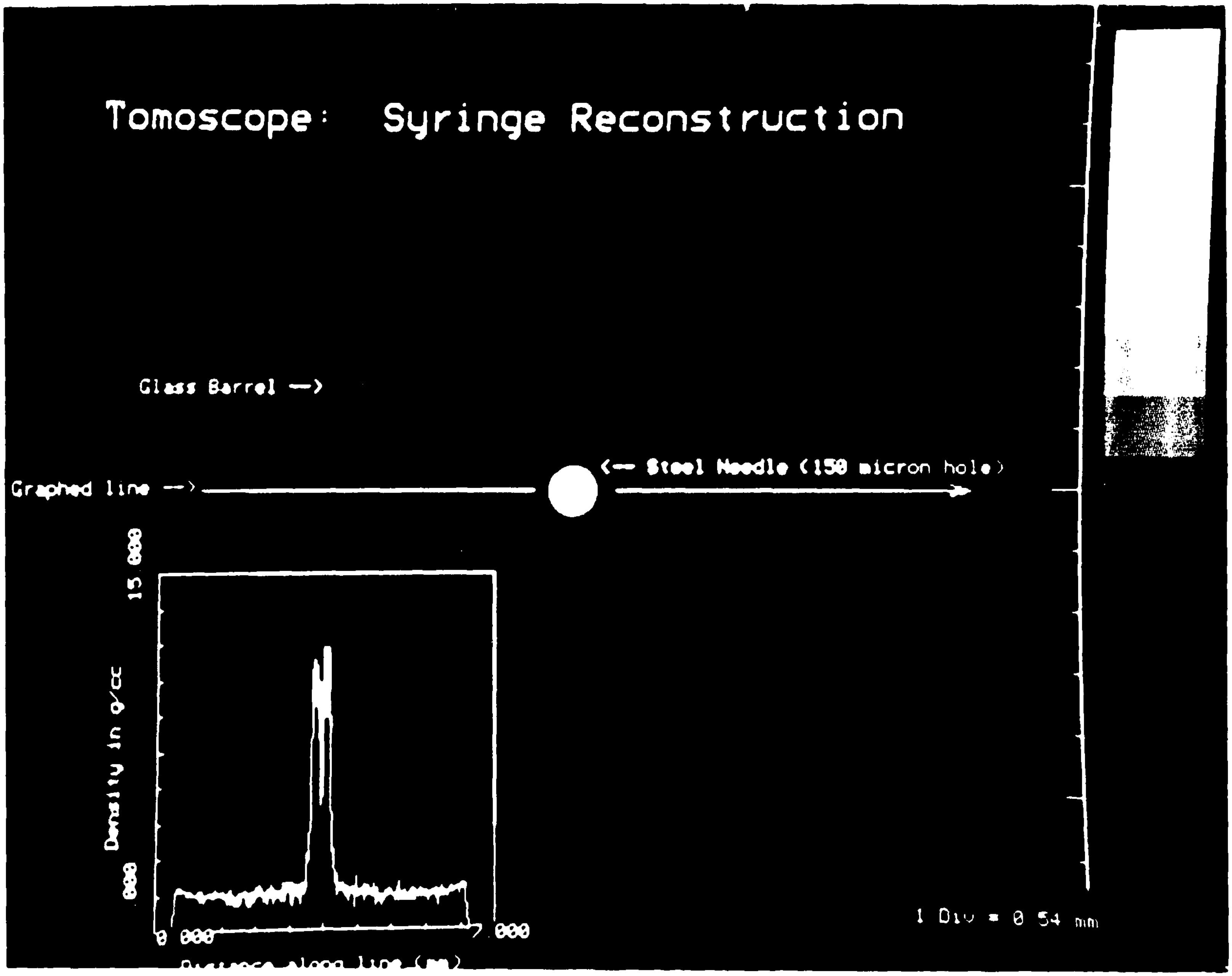

Figure 3.3 Tomoscope: syringe reconstruction

From the reconstructed image we can also estimate the mean energy of the x-ray source as seen by the SFRD. The scaling of the densities in the image is proportional to the logarithm of the local x-ray attenuation, which in turn is proportional to the local density times the mass absorption coefficient. The ratio of the steel-to-glass valuesin the reconstructed image is approximately 9. The ratio of the density of steel to the density of glass is approximately 3.3. If the steel needle were well imaged, the mass absorption coefficient for the steel would be 2.7 that of glass. Since the needle is not well imaged, the actual ratio must be greater than this value. The mass absorption coefficents of steel and glass in the photon energy region of interest are known monotonic functions of the photon energy. Thus, we can estimate the mean photon energy as between 70 and 80 keV as indicated in Section 3.1.

3.4 Summary and Implications

Some simple thermodynamic calculations lead us to conclude that, for a stationary tungsten anode and a 25-micron focal spot, the maximum electron beam power which may be used is of the order of 55 watts. This limit is essentially independent of the details of the anode construction. At this level of power density, thermal equilibrium in the vicinity of the focal spot is established in a small fraction of a second. If the power density is significantly above this level, not only does the anode surface melt immediately, but significant amounts of tungsten are vaporized. Thus at 150 kV with a 25-micron focal spot and a stationary anode, we will be limited to about a 300 microamp tube current. This implies a needed increase in sensitivity in the detector of about two orders of magnitude to provide the required signal level to the ADC.

At this point the adequacy of the Scan Ray microfocus source for imaging is an open question. The questions which need to be answered are, "With a 25-micron focal spot at a 300-microamp anode current,

...is the focal spot size and position adquately stable?"

...can the x-ray output be increased by further engineering?"

The detector sensitivity needs to be improved even if the x-ray tube output is significantly greater than indicated by these measurements. The SFRD

sensitivity can be improved by cooling the detector to reduce the dark current and dark current noise and further amplifying the signal. Several orders of magnitude improvement can be reasonably expected. In order to achieve the required amplifier stability, the video amplifiers, which utilize AC amplification with DC restoration, employed by the Reticon evaluation circuit board should be replaced with state-of-the-art DC amplifiers with precision offsets.

The SPD sensitivity can be improved by the simple expedient of integrating the signal with a few tenths of a second integration time and utilizing a higher gain transimpedance amplifier. The required circuitry for this modification can be adapted from existing ARACOR CT systems.

SECTION 4 APPLICATION STUDIES

Three potential applications for the tomoscope were identified and evaluated. They are (1) pre- and post-exposure inspection of underground test samples; (2) manufacturing control of coaxial cable and quality assurance of assembled satellite cables; and (3) acceptance screening of packaged VHSIC chips. Although application requirements and scanner performance specifications are still being defined, an initial comparison was made of the inspection requirements for each candidate application and the preliminary estimates of system performance. The results of these comparisons are presented in this section.

4.1 UGT Samples

The evaluation of pre- and post-exposure UGT samples appears to be an excellent initial application for the tomoscope. UGT samples range in size from 1-inch-diameter disks to structures as large as 6 feet long by 2 feet in diameter and include a variety of generic structures such as windows, nose tips, heat shields, rear covers and various substructures. Samples are composed of a variety of materials: carbon-carbon and carbon-phenolic composites as well as advanced ceramic composites such as silica-fiber-reinforced boron nitride. Many of these items are of a size or shape and a density which is compatible with the 4-inch circle of reconstruction and the 160-kV peak x-ray energy of the tomoscope.

An additional factor favoring an early usage of the tomoscope for UGT samples is the relatively low volume of material to be inspected. Typically, an underground test is conducted once every year or two and produces a total of about 10 to 20 square feet of exposed material. A single instrument should be able to handle the entire inspection load.

The defects of interest depend on the material, the construction, and the application; but the types of defects that are of concern include debonds, cracks, delaminations, internal irregularities, and small permanent deformations. It is believed that a tomoscope with a spatial resolution on the

order of 50 microns would be able to successfully elicit these types of defects. The hope is that once experience has been gained with the tomoscope, the costly (and destructive) process of cutting and polishing UGT samples to assess material integrity could be eliminated.

One specific and immediate application for the tomoscope is the inspection of antenna windows. These critical items present a unique inspection challenge for the tomoscope because they are ring-like structures much larger than the 4-inch circle of reconstruction of the instrument. Fortunately, the region of interest is oriented in such a manner that it can fit within the given field of view as shown in Figure 4.1. This can be accommodated without any modifications to the conceptual design as illustrated in Figure 4.2. This unusual approach is dictated by the technology: CT demands 180° of unrestricted access to the section being inspection. In the case at hand, the only way to obtain a full set of views with the proposed system, without major engineering changes, is to use the unorthodox method sketched in Figure 4.2.

4.2 Coaxial Cable SGEMP Response

The SGEMP response of shielded coaxial cables is directly related to the presence of gaps between the conductor and the dielectric. Since dielectrics are usually extruded onto the inner wires, such gaps commonly arise at the shield-dielectric interface. The SGEMP response of cables can be characterized by means of a continuous x-ray source. This technique, however, is unable to provide any accurate information within the cable.

The proposed x-ray tomoscope offers an ideal means to non-invasively and non-destructively obtain previously unavailable quantitative information regarding the detailed nature, size and distribution of the gaps and voids which are present in a cable that exhibits a SGEMP response. Such information could be of significant value to the DNA in contributing to a greater understanding of the phenomena. The proposed x-ray tomoscope could be incorporated into a system that would offer the DNA a new on-line cable inspection/measurement capability for a laboratory or manufacturing environment. Such a system, conceptually, could furnish a means of inspecting cable by continuously measuring the cable's

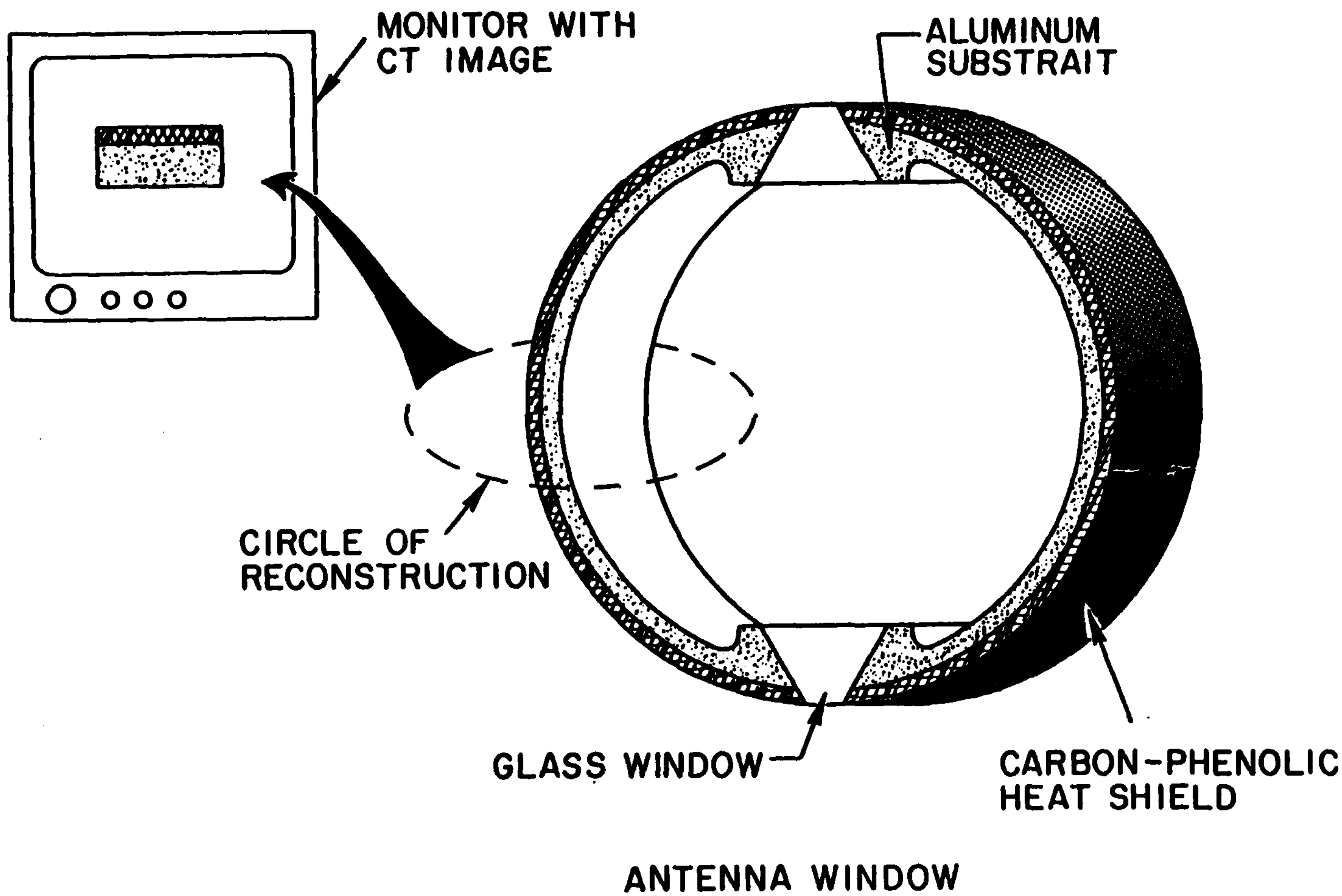

Figure 4.1 Relative position and orientation of image plane

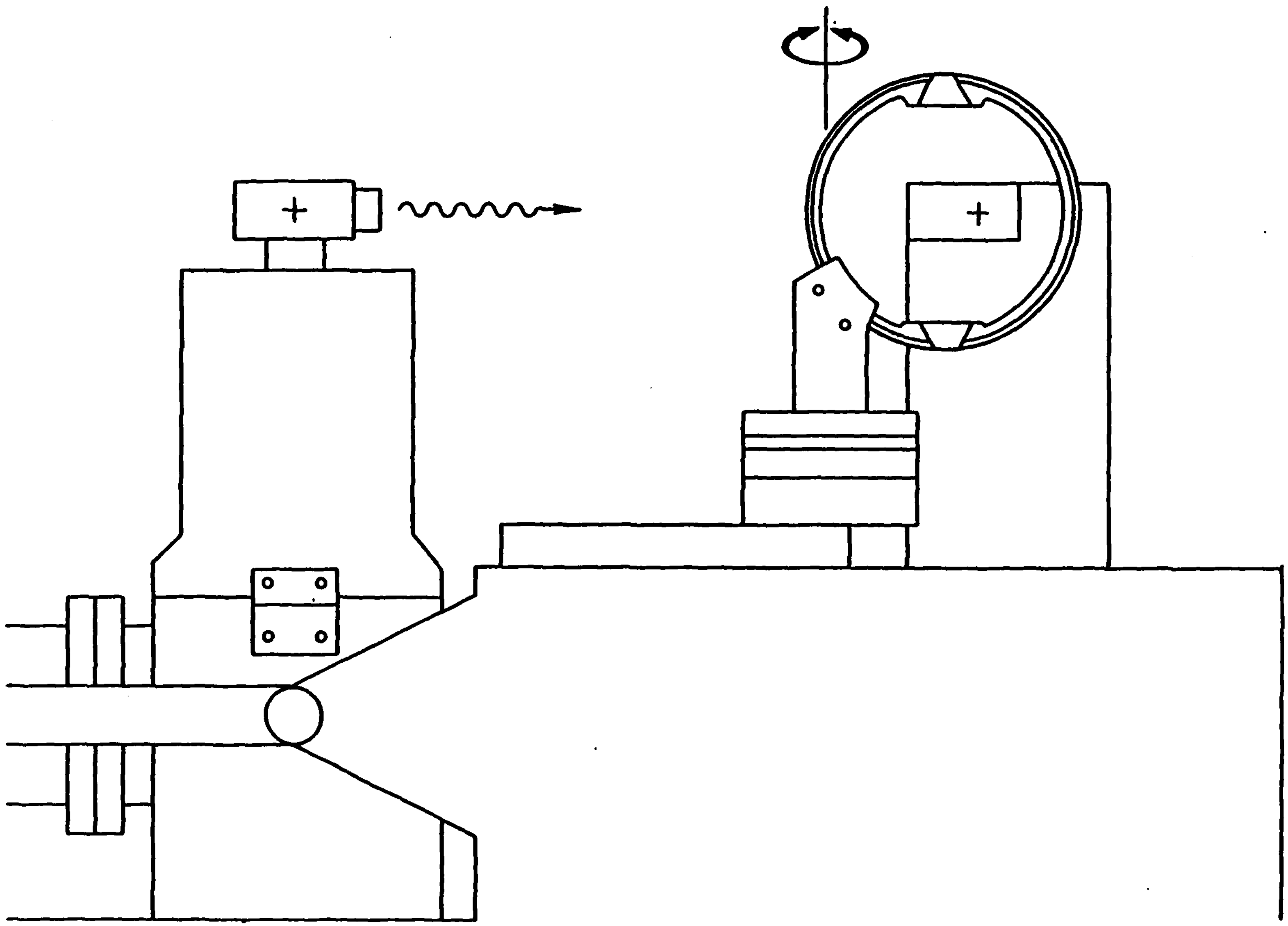

Figure 4.2 Tomoscope inspection of antenna windows

SGEMP response while the cable is fed through the system. The system's x-ray source could be collimated so as to irradiate only a narrow section of the cable to provide selectivity in identifying the spatial location of any resulting SGEMP response. Transport of the cable through the system would be halted whenever a SGEMP response of a selected magnitude occurs. At that time, the system would conduct a detailed tomoscopic examination of the suspected region to provide quantitative information regarding the nature and spatial location of the gaps and voids within the cable that contribute to the observed SGEMP response at that particular location. It is believed that an x-ray tomoscope incorporated into such an on-line measurement/inspection system would offer the DNA a capability of significant importance for further characterizing and understanding the SGEMP response of coaxial cables.

To be useful for satellite cable inspections, the tomoscope would need to be capable of detecting 5-micron gaps between the braid and the dielectric of the cable. Although 5-microns exceeds the current spatial resolution capabilities of the tomoscope, CT instruments are able to detect flaws considerably smaller than their resolution limits. Based on sound estimates, the tomoscope should be able to detect 5-micron gaps. However, detecting small flaws near sharp materials boundaries (i.e., near the braid-dielectric interface) is difficult for any radiographic technique, including CT. Thus, the ability of the tomoscope to provide a useful inspection modality is still uncertain at this stage and needs to be explored further.

If a useful inspection capability can be demonstrated, a special specimen handling device will have to be designed. Uncut cable, the primary inspection application, is supplied in long (approximately 1100') segments on spools several feet in diameter. Some type of assembly to feed cable to the scanner, rigidly freeze the section under inspection, and advance the spool after each image will need to be devised. One possible conceptual approach is illustrated in Figure 4.3.

The cable is fed through the system from the original spool to a take-up spool in discrete step sizes determined by the operator. After each advancement of the cable, the apparatus holds the section to be imaged fixed with respect to the table while simultaneously allowing the scanner the freedom of movement it requires to perform a scan. The lucite cylinder provides mechanical support without interferring with the data collection process.

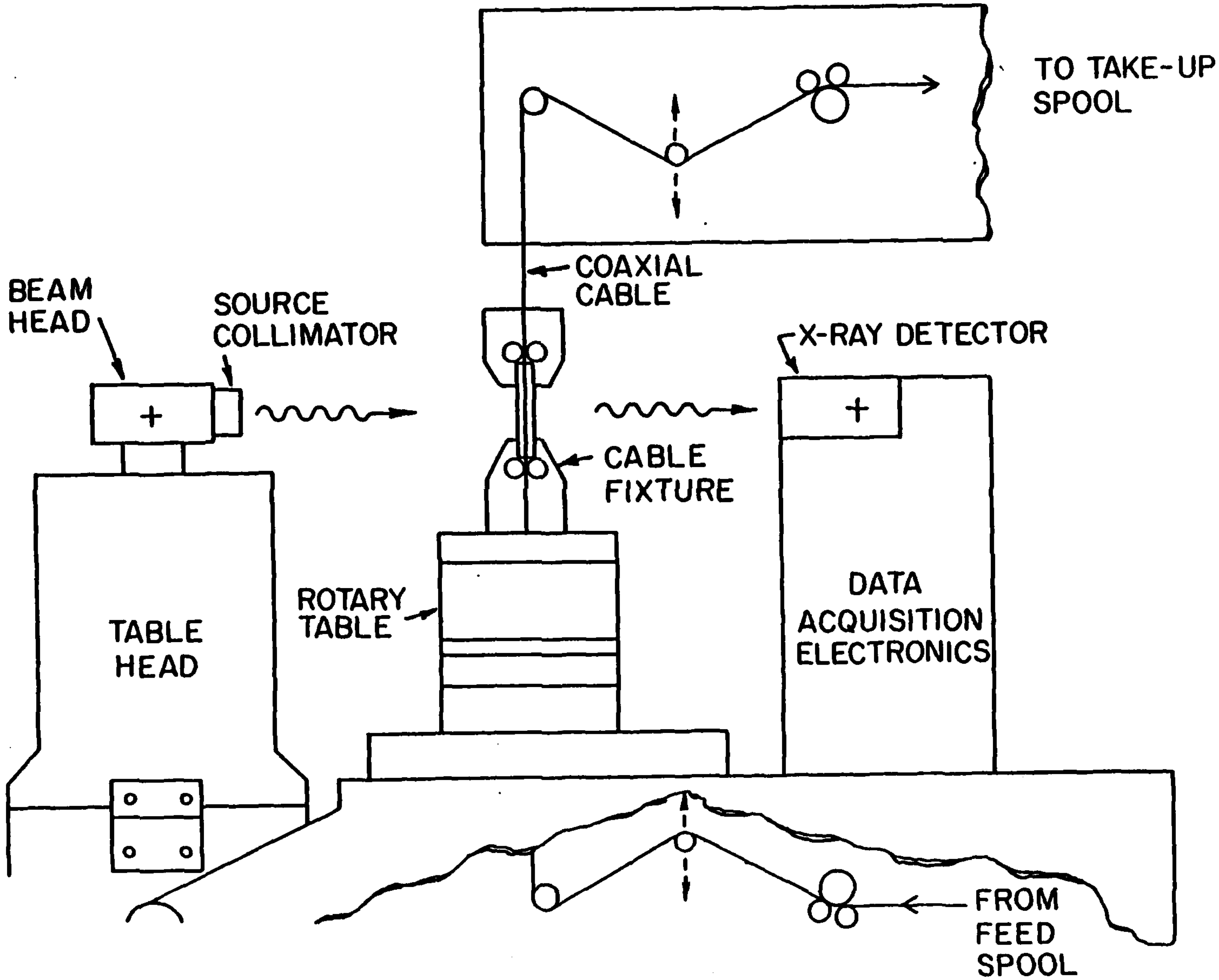

Figure 4.3 Tomoscope inspection of coaxial cable

4.3 VHSIC Packages

The largest number of leads which can be located on the periphery of a reasonably sized IC package appears to be in the mid-eighties. VHSIC packages, which require a much larger number of I/Os, have typically put the additional leads inboard, providing current package pin counts extending up to 244.

Unfortunately, inspection of interior solder joints is very difficult. Infared thermal-decay methods have been considered, but they require large sample sizes to calibrate, exacting set-up procedures, and skilled data interpretation. Sonic scan methods lack definition and require immersion in a coupling fluid. Normal x-ray photographs show metal coverage but not via voiding, while visual inspection procedures are simply not practical. The situation will be even worse for the Submicron VHSIC program where pin counts and performance requirements will increase still further. Thus, to a large extent, the success of the VHSIC program depends on the development of a rapid nondestructive technique which can determine solder joint quality.

The tomoscope appears to offer a possible, if not ideal, method of performing VHSIC package inspections. Whether open-via or pad-grid chip carriers are employed, a tomoscope should be capable of inspecting hidden vias or pads, outside joints, and thermal sinks to ensure they have been properly soldered, are free of microcracking and voiding, and do not contain entrapped organic debris. Spatial resolution on the order of 50 microns is believed to be adequate to achieve these inspection capabilities, a figure well within the theoretical performance of the instrument.

4.4 High-Temperature Materials for Advanced Gas Turbines

The Air Force has a strong interest in developing high-temperature structural materials for various system applications. A key application is for turbine engine parts where materials are operating at or near their capacity with respect to stress, temperature, and environment. In addition, new systems are under development which will place even greater demands on components.

Advanced high temperature materials are being sought which exhibit longer life and higher reliability than current structures and are resistant to environmental attack and catastrophic failures. Some of the important materials being studied include (1) monolithic ceramics: Si_3N_4, SiC, Mullite; (2) ceramic-ceramic composites: matrices including glass-ceramics, Mullite, reaction bonded Si_3N_4 and fused silica reinforced with various ceramic fibers whiskers, and particulates; and (3) intermetallics: aluminides of Ti, Fe, and Ni. These materials are being developed especially for structural applications such as turbine engine blades, vanes, disks, other static parts, and radomes.

The tomoscope offers a unique, convenient, and non-destructive method of characterizing cracks, microstructures, and failure modes in high-temperature structural materials. In ceramic materials, flaws are generally in the form of pores or pore agglomerates, large grains, unreacted or unsintered materials, inclusions of foreign material, surface chipping and gouging due to machining, and flaked, glassy or fibrous bands of material. The sizes of these flaws naturally vary considerably, but the most critical flaws can be of a size as small as 25 microns. This is within the theoretical performance limits of the tomoscope.

In practice, the improvement of material systems is an iterative process. The rate of progress is intimately related to the understanding of the properties and behavior of these advanced materials as a function of their microstructure. An inspection method is needed to facilitate the emergence of this understanding. Once a working version of the tomoscope has been developed, the Air Force will have a powerful NDE instrument for more rapidly and accurately elucidating the micromechanics of failure modes, the propagation of crack-microstructure interactions, and the interpretation of test data. In short, the improvement of material systems is, in a very real sense, strongly dependent on the timely development of an instrument with the capabilities of the tomoscope.

4.5 Conclusions

Several urgent inspection applications exist for the tomoscope, but all require performance capabilities near the limits of the current state of the art. Given the necessity of solving the inspection needs outlined above, it is strongly urged that actual scans of representative samples from each of the suggested categories be performed to more definitively establish whether or not and to what extent the tomoscope can satisfy these needs.

SECTION 5 CONCEPTUAL DESIGN

In this section we present a synthesis of our investigations of high resolution tomography. At this point, a design based on the rotate-only geometry using a microfocus x-ray tube, an SFRD detector array, and with a resolution goal of about 25 microns appears to be an optimal candidate for a first generation tomoscope. The pivotal issue is throughput (or scan time), which is a direct function of the current state of the art of source and detector design.

To do a reconstruction, it is necessary to obtain enough x-ray transmission data to uniquely determine the object. While some oversampling of the test object is used to reduce artifacts in the reconstruction, the amount of data required is essentially independent of scan mode. The design presented here detects most of the x rays emitted in the plane of the scan by the source by paving the detector plane with sensitive elements. Any design which sacrifices this feature will pay a corresponding price in throughput.

To achieve improvements in detector resolution would require either a significant improvement in the state of the art of SFRD detector design or abandoning the high efficiency of the SFRD approach. As the current performance of x-ray sources appears, at best, commensurate with the SFRD resolution, it is most sensible to design to present capabilities while pursuing improvements in source and detector technology in parallel.

Two additional points are worth noting. If current sources turn out not to be able to achieve 25-micron resolution, the recommended scan/detection mode will still optimize scan times. Secondly, the existence of several inspection applications at this performance level will justify the development of a prototype while allowing the accumulation of experience and technical innovation to guide the way to further improvements.

Figure 5.1 shows the geometrical layout of the tomoscope. Figure 5.2 shows how the full system might appear. In the remainder of this section we will discuss each of the functional components of a tomographic system, the level of performance required in the perspective of the proposed 25-micron rotate-only

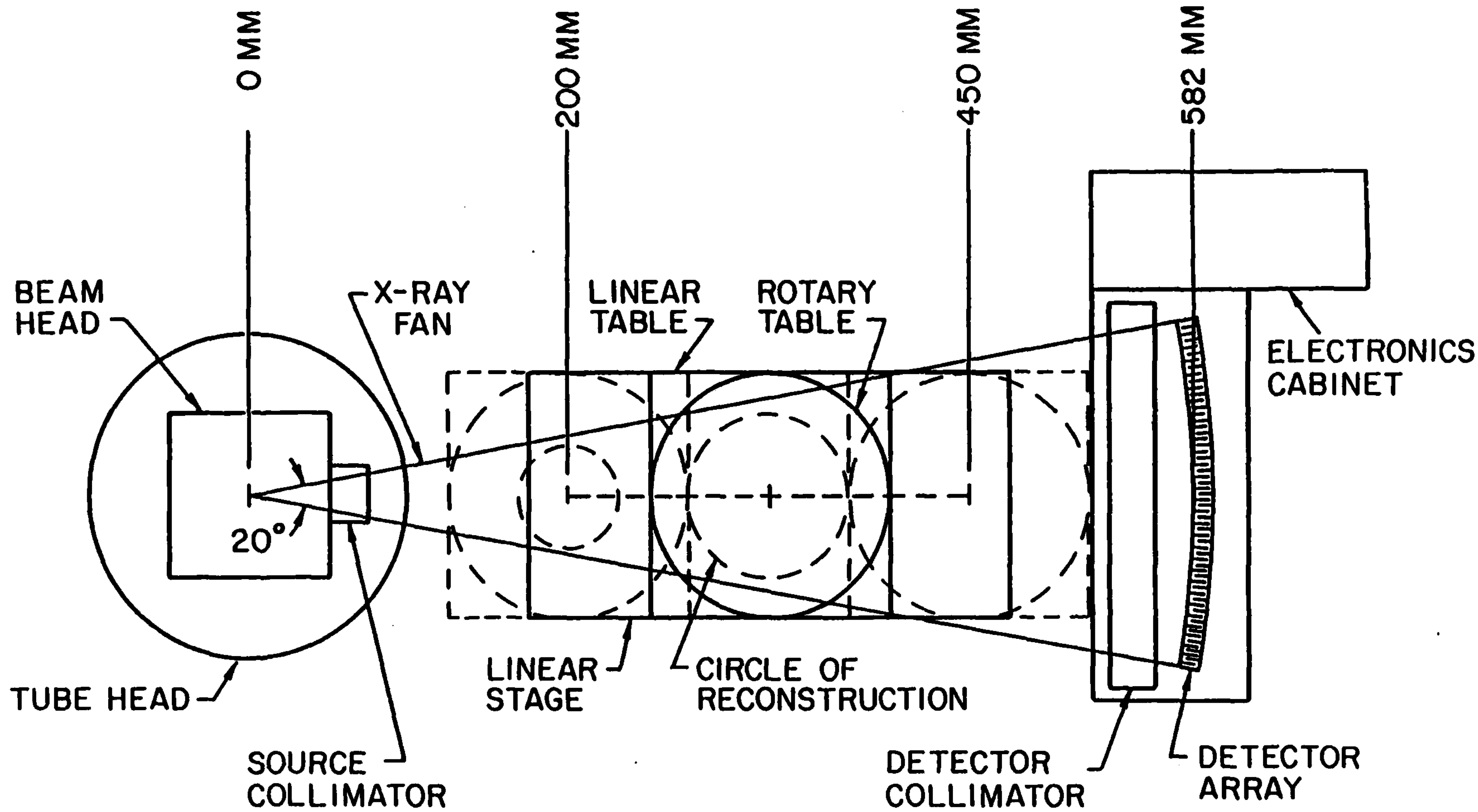

Figure 5.1 Geometrical layout of tomoscope

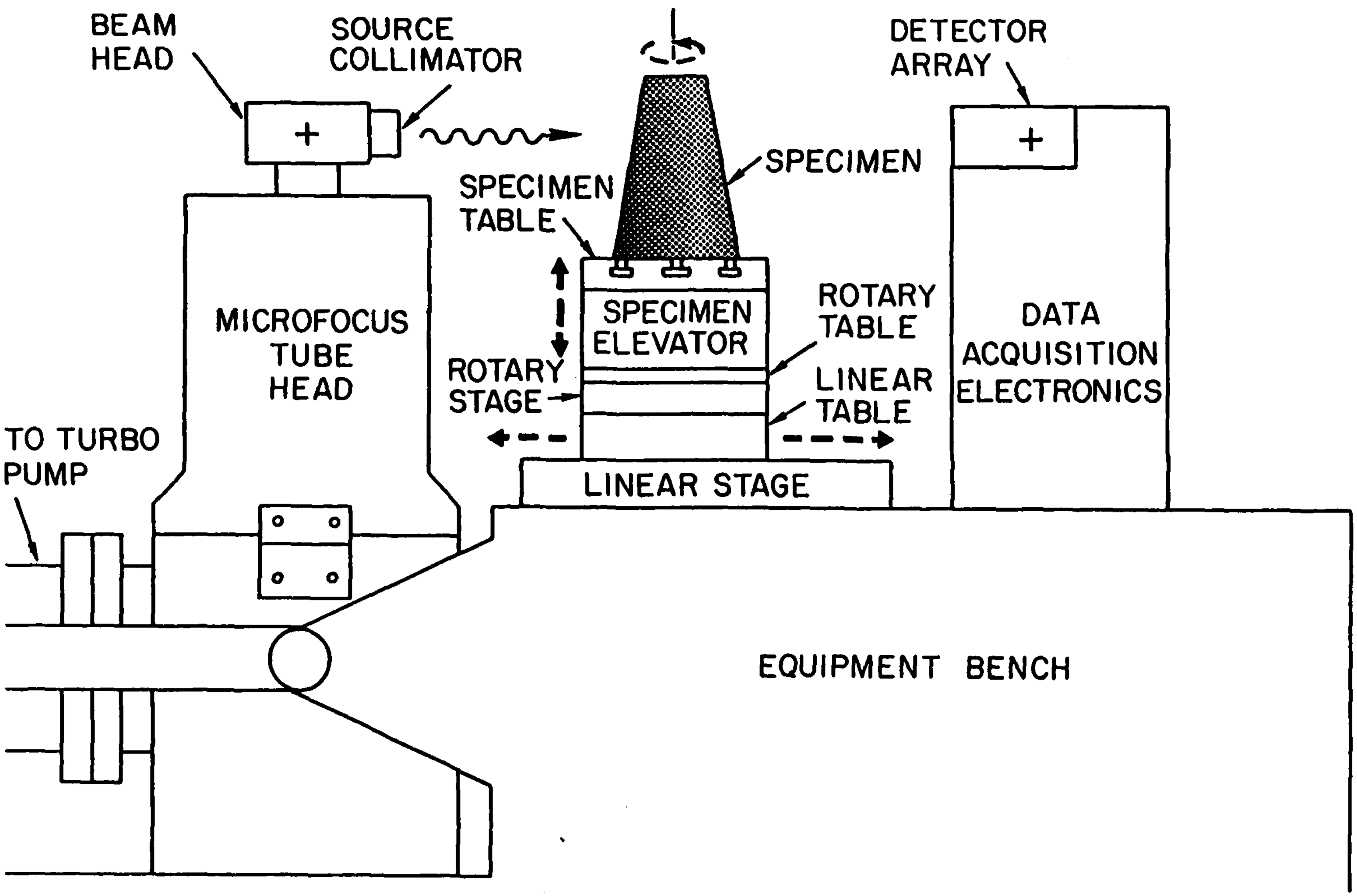

Figure 5.2 Schematic layout of tomoscope

system, and the issues to be resolved either before initiating this development or before its completion. In addition, possible approaches to achieving enhanced performance will be discussed where appropriate.

5.1 The Source

Source capabilities remain the most uncertain factors in determining the current potential for high resolution tomography. Due to the unfortunate performance of the TFI microfocus x-ray tube during our experimental evaluations, neither the intensity distribution (spot size) nor the usable intensity are adequately determined. The requisite source parameters for the proposed systems are listed below:

Anode Potential: 100 - 200 kV.

150 kV is the nominal operating voltage for the design parameters. Lower voltages would maintain contrast for scans of lower density objects. Higher voltages would allow operation with more dense objects or at higher data rates with some loss of contrast and resolution.

Tube Current: 0.1 - 2 mA.

Nominal operation appears to be limited to 0.3 mA at the present for a 25-micron spot. Lower current would be used with smaller spot size or at higher voltage to protect the anode--higher current at lower voltage or larger spot sizes.

Focal-Spot Size (including positional stability): 10 - 100 microns.

A nominal 25-micron spot is needed to meet the 25-micron resolution goal. An estimated 80% of the intensity should lie within that diameter. If the spot size can be successfully varied, additional flexibility would be possible.

Fan Angle: 20 degrees.

In a rotate-only system, the object of interest must be illuminated by the x-ray fan. A fan angle less than 20 degrees limits the size of objects that can usefully be inspected. A fan angle greater than 20 degrees might have some advantages but leads to other design problems. Twenty degrees is a good compromise for present purposes.

Shuttering:

Some mechanism will be required to shutter the x-rays when the detector is being calibrated or the scanner is in standby but otherwise idle.

The first step in developing the tomoscope is reevaluation of the source and detector parameters. Spot size and stability is particularly critical. After adquate focal properties are assured, the anode geometry should be engineered for tomoscope applications. The TFI anode and window geometry can be easily modified without affecting the electron optics.

Given that instrumental throughput is limited by photon statistics in the source, and that the maximum source intensity is set by the load limit of the anode (see Section 3.4), it is clear that reductions in scan times or improvements in resolution without substantially impacting throughput will require major upgrades in source technology.

One approach would be the development of a rotating anode x-ray tube. While this technique complicates the source design, it has been used successfully in medical CT sources for many years with outstanding results.

A second approach is to spread the anode current out over a greater area. The present source design incorporates steering coils which control the spot position. By driving these coils with a high frequency sawtooth, the spot could be driven along a line parallel to the viewing direction without significantly broadening the apparent spot size.

With suitable development, the source output could be increased by a factor of 10 to 100. We recommend that source development proceed in parallel with development of the prototype tomoscope, but that the prototype rely on current source capabilities to avoid impacting early deployment of the prototype.

5.2 The Detector

The proposed design will use the scintillator/fiber-optic Reticon detector which was investigated in the eperimental studies discussed above. The x rays are absorbed in a scintillator-loaded fiber-optic block consisting of 15-micron fibers spaced by 25-microns. The optical scintillations are detected by a Reticon array having 1024 elements on 25-micron centers. The design requirements for the detector array are listed below:

Sensitivity. The detector should be capable of detecting most of the available source photons transmitted through the sample. The dark current and noise should be low enough that measurement efficiency is, in effect, limited only by photon statistics in the signal.

The experimental measurements at TFI indicated that most of the photons were being detected with the expected signal levels. Also no stability problems occurred and the dark current was at the expected level. In order to reduce noise and dark current sufficiently to operate in a photon statistics mode, it will be necessary to cool the Reticon to -40°C and use low-noise amplifiers on the output signal. Amplifiers suitable for this purpose have been developed.

Resolution. The detector resolution should be at least 25 microns with at least 100:1 contrast.

As the experimental source problems prevented obtaining an empirical point-spread functions for this detector, we have developed a simple model to calculate this function. This model, presented in Appendix A, demonstrates that it should be possible to deconvolve the response to give 25-micron resolution in the detector array with the required contrast.

5.3 The Handling System

The prototype tomoscope is envisioned as a general purpose instrument. It will be required to investigate a wide variety of test objects as flexibly as possible to develop an understanding of what defects and microstructure can be seen and what the optimal scan technique is for each situation. Thus, the two requirements for the handling system will be flexibility and precision.

To satisfy flexibility, the system will need a variety of general purpose holding/mounting fixtures to mount the object in the desired scan orientation without interfering with the line-of-sight between the source and detectors. The mounting table will require a precision X-Y table to center the object within the circle of reconstruction and a rotary table for the scan motion. The mounting surface of the table will provide for easy attachment of special purpose jigs when necessary.

To avoid aritifacts in the reconstruction, all translations and rotations must be stable and reproducible such that any point in the test object is within approximately one micron of its desired location.

5.4 Data Acquisition

The data acquisition system will control the handling system, digitize and preprocess the detector signals, and transmit the data to the main computer for reconstruction.

The digitizers must be able to convert the 8196 data elements with 14-bit precision in periods as short as 100 msec (for rapid scanning of small objects). The optimum strategy may require using two digitizers (one per video line) on each of the eight Reticons.

Data preprocessing would include background subtraction, signal normalization, point-spread deconvolution and logarithmic reduction. A candidate for the DAS controller would be a single-board MC68000-based microcomputer. The preprocessed data would be transmitted for the main computer over a high speed data line.

5.5 Computer and Display System

Current state-of-the-art medical scanners produce 512x512 images. In the case of industrial scanners, a quantum jump to 1024x1024 is being made. With the use of array processors, fast 32-bit minicomputers and/or special-purpose CT back-projection hardware, 1024x1024 reconstruction times are in the 5-10 minute range. Because the number of additions required during back-projection increases as the number of pixels in the image matrix times the number of angular views (which must be increased for finer images), reconstruction times increase as the cube of the linear image size. Thus, using current state-of-the-art hardware, a full 4096x4096 reconstruction would require 5-10 hours (i.e., 64 times as long as for a 1024x1024 reconstruction). Since a full reconstruction under these circumstances is impractical (unless theoretically faster Fourier-space algorithms become practical), it is suggested that reconstructions be performed in two steps: an initial 1024x1024 survey of the entire scanned area, followed by additional 1024x1024 zoom reconstructions for regions of interest located in the survey. Each zoom reconstruction would have resolution as good as for a full 4096x4096 image, but would cover only the region of interest.

The current design would use a 32-bit mini-computer such as a VAX 11/730 or 11/790, an array processor with a 10-to 20-Mega-flop capacity, a 400-MB hard disk, and a 1024x1024 black-and-white display. Considering the rapid rate of development in computer technology, the exact choices of hardware would be based on a survey of the available options at the time of purchase.

5.6 Software Development

Software development would be required in three areas, data acquisition, reconstruction and display.

Data Acquisition. The DAS software would control the handling systems, detector scanning, digitization and data transmission from the digitizers and to the main computer; monitor safety of personnel and equipment, and preprocess the data. The preprocessing would require algorithm development in handling the deconvolution of source and detector characteristics from the data.

Reconstruction. The reconstruction software would draw heavily on experience gained on previous systems. However, we would recommend that significant effort be directed toward the development of faster and more efficient algorithms for handling the large reconstruction arrays required by this system.

Display. ARACOR has available a broad range of flexible and sophisticated display software produced in previous CT system developments. This software would, with suitable additions and modification, provide the groundwork for the display software.

SECTION 6 CONCLUSIONS AND RECOMMENDATIONS

In surveying potential applications for the tomoscope, we have found several pressing NDE requirements specific to the DNA mission for which high resolution tomography presents a nearly ideal solution. It is our opinion, based on the nature of the tomoscope as a general purpose imaging x-ray microscope, that as the technology is developed it will prove useful in addressing a broad range of problems.

The state of the art in the key systems--source, detectors, computers--appears ripe for the development of such an instrument. The most serious questions remaining concern the capabilities of the source, in particular the quality of the focal spot. Yet there appear to be no fundamental problems involved. There has simply been no previous need for the high-contrast focus required in this application. The quality of the pseudo-scan reconstruction obtained on a severely misbehaving source is grounds for confidence in what can be accomplished.

ARACOR capabilities are well matched to the problem. ARACOR personnel have been at the frontier of CT technology since the introduction of the first U.S. scanner in 1972. Their involvement in innovative approaches to CT applications is illustrated by current projects such as the Tomoscope, Dual Energy CT, Laminography, and Backscatter Imaging Tomography. Their extensive experience in radiation diagnostic development dovetails with this CT background to present an ideal profile for innovative development.

We highly recommend that high resolution tomography be pursued at this time. The need is there and the problems are solvable. However, to achieve the design goals of section 2, that is reconstructions over a full 10 cm diameter, it will be necessary to pursue development of a higher intensity source specifically configured for this application. Therefore, we recommend that an initial prototype be developed with the following characteristics:

- o Present model of microfocal x-ray source
- o Single SFRD detector element suitably cooled and amplified
- o 12.5 mm circle of reconstruction on a 512x512 matrix
- o 25-micron resolution (void detection ~5μm).

Development of a high output source should proceed in parallel with the initial prototype development. Thus, a second generation instrument could address the full design goals of section 2.

APPENDIX
THE DETECTOR RESOLUTION MODEL

To achieve the design goal of 25-micron instrumental resolution, the detector array response must be deconvolved to approximately 25 microns. To do this, the SFRD point-spread function should be comparable to 25 microns and not vary significantly with spectral hardness. As we were unable to experimentally measure the point-spread function, we have developed a model of the energy deposition in the detector in order to calculate this response.

The model spectrum has a linearly decreasing continuous spectrum with a high-energy cutoff at 160 keV; the low-energy content is attenuated by 0.02 inches of aluminum, and the tungsten K-lines at 60 keV contain 15% of the energy. The detector absorption is taken from data supplied by the manufacturer, Synergistic Detector Designs (SDD), Mountain View, CA. The details of this data are not shown to protect the proprietary interests of the manufacturer.

The energy of the photon is partitioned into photoelectrons excited from shells with binding energy below 6 keV (binding energy neglected) and above. Above 6 keV the binding energy is removed from the excited photoelectrons and emitted as a fluorescent x ray. The electrons travel a distance represented by their CSDA range times R-BAR. We have assumed uniform energy distribution along this path. The fluorescent x rays distribute their energy isotropically with an exponentially decreasing distribution (Beer's law).

Figure A.1 shows the calculated energy deposition for an unattenuated spectrum and for a spectram attenuated by 2.5 and 9.0 g/cm^2 of iron. As the iron attenuates the signal by factors of 10 and 100, these distributions represent the extremes of spectral hardness to be anticipated.

There are several points to note. The shoulders and flat tops in Figure A.1 are artifacts of the bin structure used in the calculation. The central peak is due to energy deposition by the initial photoelectrons and Auger electrons. Deposition by fluorescent photons is seen as the low, flat plateau

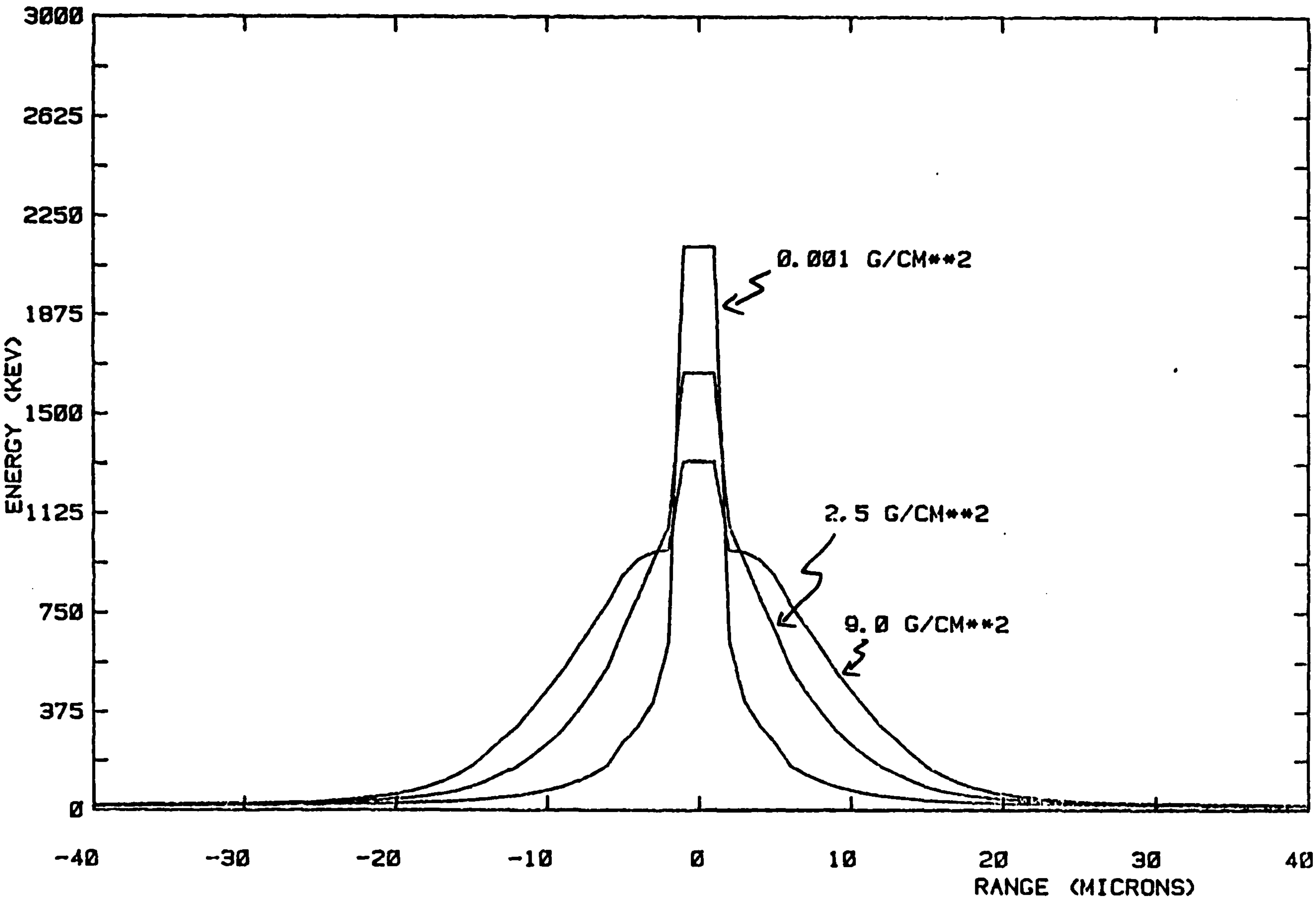

Figure A.1 Energy deposition in scintillator fiber-optic block

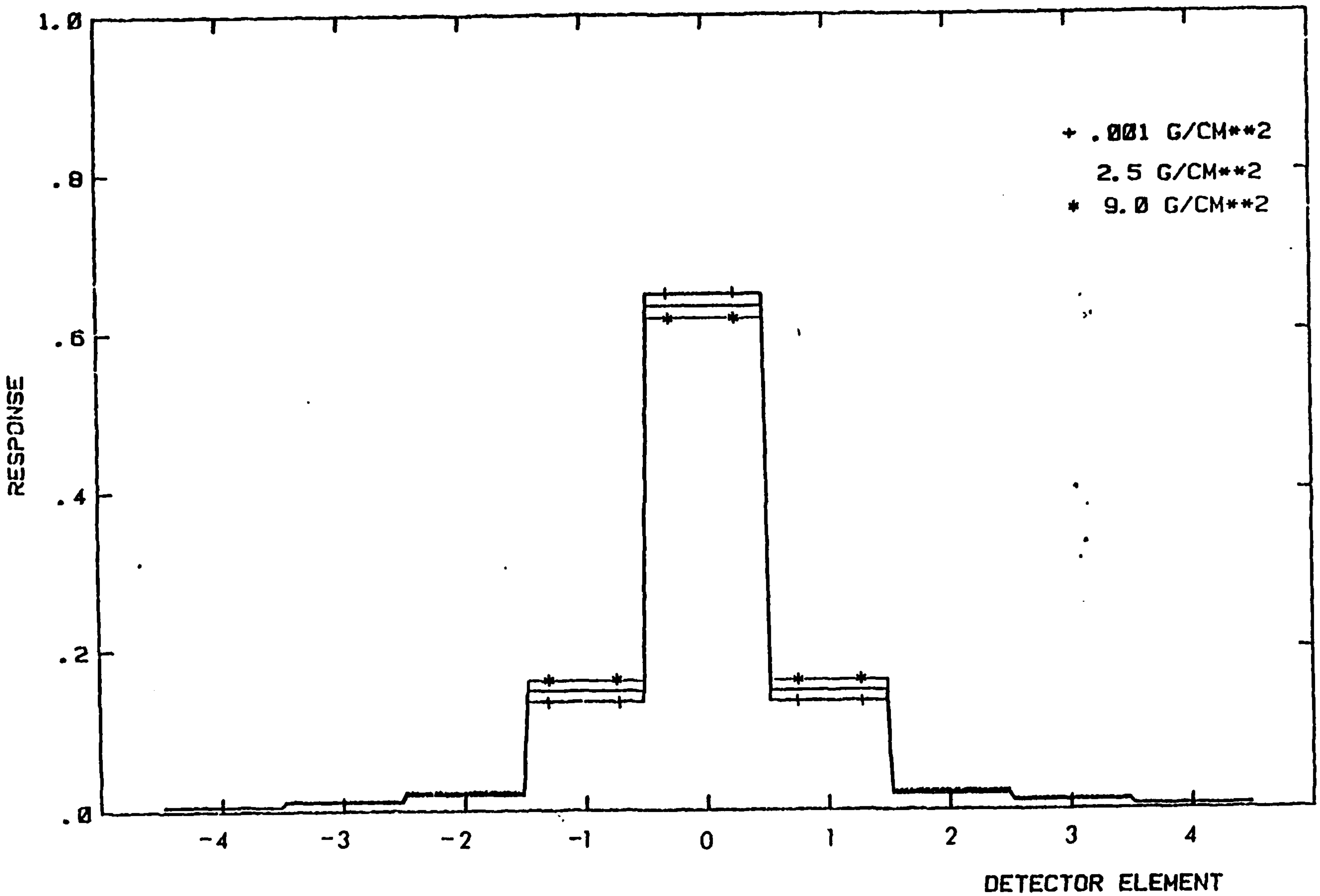

Figure A.2 Point spread function of SFRD: model

at the edges of the figure. The insensitivity of the fluorescent contribution to spectral hardness is an important outcome of the calculations. It will allow deconvolution without introducing a spectral hardness parameter in the point-spread function.

Figure A.2 shows how these distributions would appear after being collected by the Reticon array, taking into consideration the uncertain location of the initial x-ray absorption within the domain of the given Reticon pixel. Because the central peak is narrow in comparison to the 25-micron Reticon elements, the variation in peak shape nearly disappears in the final point-spread function.

While the details of the model are not expected to be exact, the essential features should be valid and give us confidence in the viability of the detector and understanding of what is to be expected. The photo-Auger contribution is narrow in comparison with the Reticon pixel, and thus the effects on the puse height distribution are not sensitive to the accuracy of the model. The fluorescent contribution is comparatively broad, but the model shape should be accurate. The critical parameter is the ratio of photo-Auger deposition to fluorescent deposition. As this parameter does not change radically for this extreme variation in spectral hardness, we should be able to successfully deconvolve the detector resolution sufficiently to achieve the design goal of 25-micron resolution in the final image.

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ATTN: NT
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ATTN: SUL
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DEPARTMENT OF THE AIR FORCE (Continued)

Air Force Technical Applications Ctr
ATTN: TAE

Air Force Wright Aeronautical Labs
ATTN: MLLP

Air University Library
ATTN: AUL-LSE

Assist Ch of Staff, Studies & Analysis
ATTN: AF/SAMI, Tech Info Div

Ballistic Missile Ofc/DAA
ATTN: ENSN

Dep Ch of Staff, Rsch, Dev & Acq
ATTN: AF/RDQI
ATTN: AFRDS, Space Sys & C3 Dir

Dep Ch of Staff, Plans & Opns
ATTN: AFXOS, Opns, Space Div

Ofc of Space Systems
ATTN: Director

Space Command
ATTN: DC
ATTN: ADCOM DE
ATTN: XPN
ATTN: XPS
ATTN: XPW

Space Division
ATTN: XR, Plans
ATTN: YDS
ATTN: YEZ
ATTN: YGJ
ATTN: YH, DSCS III
ATTN: YKF
ATTN: YKY
ATTN: YKM
ATTN: YNV

Strategic Air Command
ATTN: INAS
ATTN: NRI/STINFO
ATTN: XPFR
ATTN: XPFS

OTHER GOVERNMENT AGENCIES

Central Intell Agcy
ATTN: OSWR/STD/MTB
ATTN: Tech Library

Federal Emergency Mgmt Agcy
ATTN: FEMA Library

NASA, Lewis Rsch Ctr
ATTN: C. Purvis
ATTN: Library

DEPARTMENT OF ENERGY CONTRACTOR

Sandia National Laboratories
ATTN: Org 1232, W. Beezhold
ATTN: Org 9336, D. Allen
ATTN: Tech Lib, 3141

DEPARTMENT OF DEFENSE CONTRACTORS

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2 cys ATTN: J. Stanley
2 cys ATTN: J. LePage

Aerojet Electro-Systems Co
ATTN: SV/8711/70

Aerospace Corp
ATTN: D. Schmunk
ATTN: J. Reinheimer
ATTN: Library
ATTN: P. Hansen
ATTN: V. Josephson

Analytic Services, Inc (ANSER)
ATTN: A. Shostak

Beers Associates, Inc
ATTN: B. Beers

Berkley Rsch Associates Inc
ATTN: E. Alcarez

Computer Sciences Corp
ATTN: A. Schiff

Dikewood Corp
ATTN: Tech Library

Dikewood Corp
ATTN: K. Lee

EOS Technologies, Inc
ATTN: B. Gabbard

General Electric Co
ATTN: D. Tasca
ATTN: H. O'Donnell
ATTN: J. Peden

General Motors Corp
ATTN: MS M-101, T. Nybakken

General Research Corp
ATTN: A. Hunt

Hughes Aircraft Intl Svc Co
ATTN: A. Narevsky
ATTN: L. Darda
ATTN: N. Milin

Institute for Defense Analyses
ATTN: Classified Library

IRT Corp
ATTN: B. Williams
ATTN: Library
ATTN: N. Rudie

IRT Corp
ATTN: J. Klebers

JAYCOR
ATTN: E. Wenaas
ATTN: Library
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JAYCOR
ATTN: R. Poll

JAYCOR
ATTN: M. Bell

Kaman Sciences Corp
ATTN: D. Osborn
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ATTN: N. Beauchamp
ATTN: W. Rich

Kaman Sciences Corp
ATTN: E. Conrad

Kaman Tempo
ATTN: DASIAC
ATTN: W. McNamara

Kaman Tempo
ATTN: DASIAC

Lockheed Georgia Co
ATTN: E. Harris

Lockheed Missiles & Space Co, Inc
ATTN: L. Chase

Mission Research Corp
ATTN: C. Longmire
ATTN: M. Scheibe
ATTN: R. Stettner

Mission Research Corp
ATTN: Library

Pacific-Sierra Research Corp
ATTN: H. Brode, Chairman SAGE

Physics International Co
ATTN: D. Harmony

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R&D Associates
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ATTN: S. Siegel
ATTN: Tech Info Ctr

Rand Corp
ATTN: P. Davis

Rand Corp
ATTN: B. Bennett

Rockwell International Corp
ATTN: Library

Rockwell International Corp
ATTN: TIC D/41-092, AJ01

S-CUBED
ATTN: A. Wilson
ATTN: Library

Science Applications Intl Corp
ATTN: K. Sites

Science Applications Intl Corp
ATTN: J. Tigner
ATTN: W. Chadsey

SRI International
ATTN: M. Tarrasch

SRI International
ATTN: A. Padgett

TRW Electronics & Defense Sector
ATTN: D. Clement
ATTN: R. Kinsland
ATTN: Tech Info Ctr

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